Multihop Communications with Fixed-Gain Relays over Generalized Fading Channels

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Abstract— **Efficient performance bounds for multihop wireless communications systems with non-regenerative fixed-gain relays operating over non-identical generalized fading channels, are presented. More specifically, the end-to-end signal-to-noise ratio (SNR) is formulated and upper bounded by using the well-known inequality between harmonic and geometric mean of positive random variables. Based on this bound, the moments of the end-to-end SNR for Rayleigh, Nakagami-m, and Rice fading channels, are obtained in simple closed-forms. Furthermore, the outage performance and the average error probability for coherent and non-coherent modulation schemes are also studied using the moment-generating function (MGF) approach. The proposed method for the evaluation of the MGF is based on the Padé approximants theory. Moreover, new expressions are derived for the gain of previously proposed "semi-blind" relays. These expressions are used in numerical and computer simulations examples, to verify the accuracy and to show the tightness of the proposed bounds.**

I. Introduction

Nowadays, multihop wireless communications systems are able to provide a potential for broader and more efficient coverage in bent pipe satellites and microwave links, as well as modern ad-hoc, cellular, WLAN, and hybrid wireless networks [1, and references therein]– [5]. In a multihop network, several intermediate terminals operate as relays between the source and the destination. Generally, there are two types of such relays. If the relay just amplifies and re-transmits the information signal, it is called "non-regenerative", while when the relaying node decodes the signal and then transmits the detected version to the next node, it is called "regenerative" [6].

Published papers concerning the performance analysis of multihop wireless communications systems are scarce. Zogas *et al*. in [7], presented an analysis for the performance of dual-hop wireless communications systems with non-regenerative relays, operating over independent but not necessarily identically distributed (i.d.) Nakagami-m fading channels. Hasna and Alouini studied the outage and the error performance of dual-hop systems with regenerative and non-regenerative relays over Rayleigh [6], [8] and Nakagami-m [9] fading channels. Moreover, the same authors presented a useful and general analytical framework for the evaluation of the end-to-end outage probability of multihop wireless systems with non-regenerative channel state information (CSI)-assisted relays over Nakagami-m fading channels [10]. In these works [6]–[10], the analysis is based on an upper bound for the end-to-end signal-to-noise ratio (SNR) of the multihop system, which leads to lower bounds for the system outage and error performance. This bound corresponds to an ideal relay capable of inverting the channel in the previous hop (regardless of the fading state of that hop). Other contributions related to the performance analysis of multihop transmissions with CSI-relays are included in [11], [12], where multi-user spatial diversity is used to combat the signal's impairments due to shadowing. However, the literature is poor concerning the performance of multihop communications with fixed-gain relays. Only in [13], the end-to-end performance of dual-hop systems equipped with non-regenerative fixed gain relays is investigated. In the same paper, the authors propose a specific fixed gain relay, called "semi-blind", that benefits from the knowledge of the first hop average fading power. Furthermore, the effect of the relay saturation on the overall system's performance is also studied. However, to the best of the author's knowledge, there is not any published work concerning the performance of multihop transmissions with fixed-gain relays over generalized fading channels. This fact occurs, although these kind of relays offer simplicity and ease of deployment at the expense of performance, comparing to the CSI-assisted relays [13].

In this paper, tight performance bounds for multihop wireless communications systems with fixed-gain relays over non-identical Rayleigh, Nakagami-m and Rice fading channels, are presented. More specifically, a simple upper bound is proposed for the end-to-end SNR by using the well-known inequality between harmonic and geometric mean of positive random variables (RV)s. This bound is used to study important system performance metrics by deriving simple closed-form expressions for the moments of the end-to-end SNR. The outage performance and the average error probability for several coherent (e.g. BFSK, M-PAM, M-PSK and M-QAM) and non-coherent (e.g. BFSK and M-DPSK) modulation schemes are studied, using the well-known moment-generating function (MGF) approach [14]. The proposed method for the evaluation of the MGF is based on the Padé approximants theory. Furthermore, new expressions are derived for the gain of previously proposed "semi-blind" relays. These formulae are used in numerical and computer simulations results, to verify the accuracy of the presented mathematical analysis and to show the tightness of the proposed bounds.

II. System Model

A multihop wireless communication system is considered, operating over independent, but not necessarily i.d., fading channels. The source terminal **S** communicates with the destination terminal **D** through the $N-1$ nodes-terminals, $T_1, T_2, \ldots, T_{N-1}$, which act as intermediate relays from one hop to the next. These intermediate nodes are employed with non-regenerative relays with fixed gain, G_i, given by

$$G_i^2 = \frac{1}{C_i\, N_{0,i}}, \qquad i = 1, 2 \ldots, N-1 \tag{1}$$

where $N_{0,i}$ is the single-sided power spectral density of the additive white Gaussian noise (AWGN) at the output of the ith relay and C_i is a constant.

A. End-to-End SNR

Assuming that terminal **S** is transmitting a signal s with an average power normalized to unity, the received signal at the first intermediate node, T_1 can be written as

$$r_1 = a_1 s + n_1 \tag{2}$$

where a_1 is the fading amplitude of the channel between **S** and node T_1 and n_1 is the corresponding AWGN. The signal r_1 is then multiplied by the gain G_1 of the terminal T_1 and re-transmitted to terminal T_2, where the received signal can be written as

$$r_2 = G_1 a_2 \left(a_1 s + n_1\right) + n_2 \tag{3}$$

where a_2 is the fading amplitude of the channel between T_1 and T_2 and n_2 is the corresponding AWGN. Following the same procedure as in [10], the end-to-end SNR can be written as

$$\gamma_{end} = \frac{\prod\limits_{i=1}^{N} \alpha_i^2\, G_{i-1}^2}{\sum\limits_{n=1}^{N} N_{0,n} \left(\prod\limits_{i=n+1}^{N} G_{i-1}^2 \alpha_i^2\right)}. \tag{4}$$

Dividing both numerator and denominator with $\prod_{i=1}^{N} \alpha_i^2\, G_{i-1}^2$ and using (1) yields

$$\begin{aligned}\gamma_{end} &= \left(\frac{1}{\gamma_1} + \frac{C_1}{\gamma_1\gamma_2} + \cdots + \frac{C_1 C_2 \cdots C_{N-1}}{\gamma_1\gamma_2\gamma_3\cdots\gamma_N}\right)^{-1} \\ &= \frac{1}{N}\left(\frac{1}{N}\sum_{n=1}^{N}\frac{1}{\beta_n}\right)^{-1}\end{aligned} \tag{5}$$

where $\beta_n = \prod_{i=1}^{n} \gamma_i / C_{i-1}$ and $\gamma_i = a_i^2 / N_{0,i}$ is the instantaneous SNR of the ith hop. It can be easily recognized that γ_{end} is related to the *Harmonic Mean* of the positive RVs $\beta_1, \beta_2, \ldots, \beta_N$ with

$$\gamma_{end} = \frac{1}{N}\,\mathcal{H}_N^{\beta_n} \tag{6}$$

where

$$\mathcal{H}_N^{x_n} \triangleq \left(\frac{1}{N}\sum_{n=1}^{N}\frac{1}{x_n}\right)^{-1} \tag{7}$$

is defined as the *Harmonic Mean* of the N positive RVs x_i.

B. Upper Bound for the End-to-End SNR

Unfortunately, (5) cannot be used to derive closed-form expressions for several performance metrics of the multihop system under consideration. In order to overcome this problem, γ_{end} is bounded using the well-known inequality between the geometric and the harmonic mean of N positive RVs [16]

$$\mathcal{H}_N^{x_n} \le \mathcal{G}_N^{x_n} \tag{8}$$

with

$$\mathcal{G}_N^{x_n} \triangleq \left(\prod_{n=1}^{N} x_n\right)^{1/N} \tag{9}$$

being the *Geometric Mean* of the N positive RVs x_i. The equality in (8) holds only for $x_1 = x_2 = \cdots = x_N$. Using (6) and (8) and after some mathematical manipulations, an efficient and simple upper bound, γ_b, for the end-to-end SNR is obtained as

$$\gamma_{end} \le \gamma_b = \mathcal{Z}_N \prod_{i=1}^{N} \gamma_i^{\frac{N+1-i}{N}} \tag{10}$$

where $\mathcal{Z}_N$ is a constant related to the introduced fixed-gains, given by

$$\mathcal{Z}_N = \frac{1}{N}\prod_{i=1}^{N} C_i^{-\frac{N-i}{N}}. \tag{11}$$

The form of γ_b has the advantage of mathematical tractability over that in (5). Furthermore, as it will be shown in the next sections, it is a tight upper bound for γ_{end}, which can be efficiently used to study the end-to-end performance of the multihop system.

III. Moments of the End-to-End SNR

The first and the second order moments of the end-to-end SNR are statistical parameters which can be efficiently used to evaluate important performance measures, such as average output SNR and variance. Higher order moments (i.e., third and above) are also useful in signal processing algorithms for signal detection, classification, and estimation and can play a fundamental role in understanding the performance of wide-band communications systems in the presence of fading [17]. Using the well-known inequality for positive RVs, $\gamma_{end} \le \gamma_b \Rightarrow E\left\langle \gamma_{end}^k \right\rangle \le E\left\langle \gamma_b^k \right\rangle$, where $E\left\langle \cdot \right\rangle$ denotes expectation and due to the independency of $\gamma_1, \gamma_2, \ldots, \gamma_N$, the kth moment of γ_{end} can be bounded as

$$\begin{aligned}E\left\langle \gamma_{end}^k \right\rangle \le E\left\langle \gamma_b^k \right\rangle &= \mathcal{Z}_N^k E\left\langle \prod_{i=1}^{N} \gamma_i^{\frac{k(N+1-i)}{N}} \right\rangle \\ &= \mathcal{Z}_N^k \prod_{i=1}^{N} E\left\langle \gamma_i^{\frac{k(N+1-i)}{N}} \right\rangle.\end{aligned} \tag{12}$$

Rayleigh / Nakagami-m Fading: Assuming that the multihop system operates in Nakagami-m fading environment, then γ_i is a gamma distributed RV with $E\left\langle\gamma_i^k\right\rangle$ given by [14, eq. (2.23)]

$$E\left\langle\gamma_i^k\right\rangle = \overline{\gamma}_i^k \frac{\Gamma\left(m_i+k\right)}{\Gamma\left(m_i\right)m_i^k} \tag{13}$$

where m_i is the Nakagami-m parameter describing the fading severity of the ith hop and $\Gamma\left(\cdot\right)$ is the Gamma function [18, eq. (8.310.1)]. Using (12) and (13), $E\left\langle\gamma_b^k\right\rangle$ can be written in closed-form as

$$E\left\langle\gamma_b^k\right\rangle = \mathcal{Z}_N^k \prod_{i=1}^{N}\left\{\left(\frac{\overline{\gamma}_i}{m_i}\right)^{\frac{k(N-i+1)}{N}} \frac{\Gamma\left[m_i+\frac{k(N-i+1)}{N}\right]}{\Gamma\left(m_i\right)}\right\}. \tag{14}$$

Setting $k=1$ in (14), an upper bound for the average end-to-end SNR in (5) can be derived.

Rice Fading: The Rice distribution includes the Rayleigh distribution as a special case and provides optimum fit to collected data for mobile satellite, as well as indoor and outdoor and applications [14]. When the fading amplitude a_i follows the Rice distribution, then γ_i is a non-central chi-square distributed RV with $E\left\langle\gamma_i^k\right\rangle$ given by [14, 2.18]

$$E\left\langle\gamma_i^k\right\rangle = \overline{\gamma}_i^k \frac{\Gamma\left(1+k\right)}{\left(1+K_i\right)^k}\,{}_1F_1\left(-k,\;1;\;-K_i\right) \tag{15}$$

where K_i is the Rice factor at the ith hop, which ranges from 0 to ∞ and ${}_1F_1\left(\,\cdot\,,\,\cdot\,;\,\cdot\,\right)$ is the confluent hypergeometric function of the first kind [18, eq. (9.210/1)]. Using (12) and (15), the moments of the bound γ_b can be expressed in closed-form as

$$E\left\langle\gamma_b^k\right\rangle = \mathcal{Z}_N^k \prod_{i=1}^{N}\left[\left(\frac{\overline{\gamma}_i}{1+K_i}\right)^t \Gamma\left(1+t\right)\,{}_1F_1\left(-t,\,1;\,-K_i\right)\right] \tag{16}$$

where $t=k\left(N-i+1\right)/N$. An upper bound for the average end-to-end SNR in (5) can be derived using (16) with $k=1$.

IV. Padé Approximants and Average Error Rates

Padé approximants is a simple and efficient method to approximate the MGF and in sequel to evaluate average error rates using the well-known MGF-based approach [14]. The main advantage of this approach is that due to the form of the produced rational approximation, the error rates can be calculated directly using simple expressions for the non-coherent BFSK and DPSK modulation schemes, while for other modulation schemes, including M-QAM and M-PSK types, single integrals with finite limits and integrands composed of elementary functions can be readily evaluated by numerical integration. The MGF of γ_b is defined as $\mathcal{M}_{\gamma_b}(s) \triangleq E\left\langle e^{s\,\gamma_b}\right\rangle$ and can be represented as a formal power series (e.g. Taylor)

$$\mathcal{M}_{\gamma_b}\left(s\right) = \sum_{k=0}^{\infty}\frac{1}{k!}E\left\langle\gamma_b^k\right\rangle s^k = \sum_{k=0}^{\infty}\frac{\mu_k}{k!}s^k \tag{17}$$

where $\mu_k = E\left\langle\gamma_b^k\right\rangle$. Although the moments of all orders are finite and can be evaluated in closed-form using the analysis of Section III, in practice only a finite number Q can be used truncating the series in (17) as

$$\mathcal{M}_{\gamma_b}\left(s\right) \cong \sum_{k=0}^{Q}\frac{\mu_k}{k!}s^k + O\left(s^{Q+1}\right) \tag{18}$$

with $O\left(s^{Q+1}\right)$ being the remainder after the truncation. In many cases, it is not certain that the power series in (17) has a positive radius of convergence and whether or not convergences. Hence, we have to obtain the best approximation to the unknown underlying function $\mathcal{M}_{\gamma_b}(s)$ evaluating only a finite number of the moments. This can be efficiently achieved using the Padé approximation method, which has been already used in several scientific fields to approximate series as that in (17), where practically only few coefficients are known and the series converges too slowly or diverges [15]. Padé approximation was also proposed in the past to approximate unknown probability density functions (PDF)s and cumulative distribution functions (CDF)s in radar analysis [19], [20] and recently, to study the performance of equal-gain receivers [21]. A Padé approximant, is that rational function approximation to $\mathcal{M}_{\gamma_b}(s)$ of a specified order Φ for the denominator and Θ for the nominator, whose power series expansion agrees with the order power expansion of $\mathcal{M}_{\gamma_b}(s)$ [15]. The rational function

$$\mathcal{R}_{[\Theta/\Phi]}(s) \equiv \frac{\sum_{i=0}^{\Theta}\theta_i\,s^i}{1+\sum_{i=1}^{\Phi}\phi_i\,s^i} \tag{19}$$

is said to be a Padé approximant to the series (17), where θ_i and ϕ_i are real constants [21].

V. Outage Probability

If γ_{th} is a specified threshold ratio, then for non-regenerative multihop transmissions the outage probability is defined as the probability that the instantaneous SNR of the received signal at terminal **D** falls below γ_{th} [10], i.e.,

$$P_{out} = F_{\gamma_{end}}(\gamma_{th}) = \Pr\left[\gamma_{end} \le \gamma_{th}\right] \tag{20}$$

where $F_{\gamma_{end}}\left(\cdot\right)$ is the CDF of γ_{end}. When, instead of γ_{end}, the bound γ_b is used, the outage probability is bounded as

$$P_{out} = F_{\gamma_{end}}(\gamma_{th}) \ge F_{\gamma_b}(\gamma_{th}). \tag{21}$$

Moreover, if Padé approximants is used to determine $F_{\gamma_b}(\gamma_{th})$ from $\mathcal{M}_{\gamma_b}(s)$, then [10]

$$P_{out} = \mathcal{L}^{-1}\left[F_{\gamma_b}(x)/x\right]_{x=\gamma_{th}} \tag{22}$$

where $\mathcal{L}^{-1}\left(\cdot\right)$ denotes the inverse Laplace transform. Taking into account that [21]

$$\mathcal{M}_{\gamma_b}\left(s\right) \cong \frac{\sum_{i=0}^{\Theta}\theta_i\,s^i}{1+\sum_{i=1}^{\Phi}\phi_i\,s^i} = \sum_{i=1}^{\Phi}\frac{q_i}{s+p_i} \tag{23}$$

and using the residue inversion formula [19], a bound for the outage probability is derived as

$$P_{out} \ge F_{\gamma_b}(\gamma_{th}) = \sum_{i=1}^{\Phi}\frac{q_i}{p_i}e^{-p_i\,\gamma_{th}} \tag{24}$$

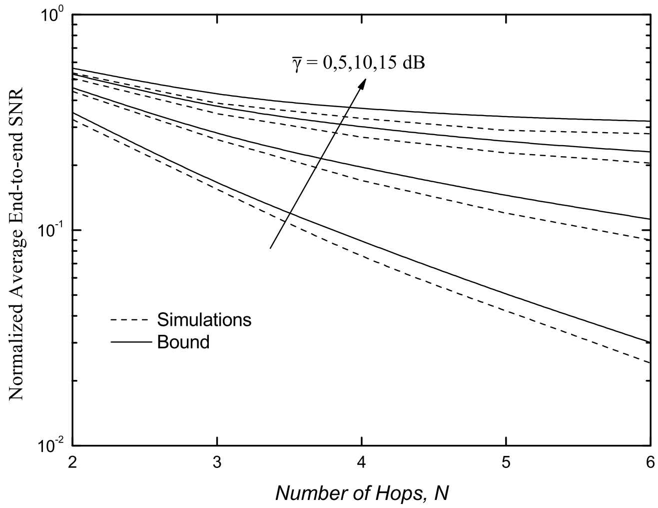

Fig. 1. Normalized average SNR versus the number of hops N in Nakagami-m fading with $m = 3$.

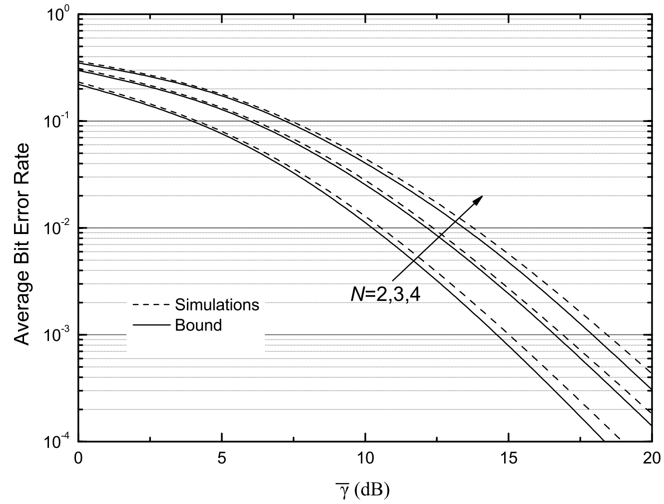

Fig. 2. Error performance for BPSK in Nakagami-m fading with $m = 3$.

where $\{p_i\}$ are the poles of the Padé approximant to $\mathcal{M}_{\gamma_b}(s)$, which must have negative real part and $\{q_i\}$ are the residues [19], [20].

VI. A Class of "Semi-Blind Relays" in Generalized Fading Channels

In this section, new expressions for the gain of a -previously published- class of "semi-blind" relays are presented in closed and analytical forms for Rayleigh Nakagami-m and Rice fading, respectively. Hasna and Alouini [13] proposed a class of "semi-blind" relays which consume the same average power with the corresponding CSI-based relays. The relay gain of this "semi-blind" scenario is chosen as

$$G_i^2 = E\left\langle \frac{1}{a_i^2 + N_{0,i}} \right\rangle = \int_0^\infty \frac{f_{a_i}(a_i)}{a_i^2 + N_{0,i}} da_i \qquad (25)$$

with $f_{a_i}(\cdot)$ being the PDF of the ith hop's fading amplitude. For Rayleigh fading channels G_i^2 can be written as

$$G_i^2 = \frac{e^{1/\overline{\gamma}_i}\,\Gamma(0, 1/\overline{\gamma}_i)}{\overline{\gamma}_i N_{0,i}} \qquad (26)$$

where $\Gamma(\cdot,\cdot)$ is the incomplete Gamma function [18, eq. (8.350/2)], defined as $\Gamma(x,y) \triangleq \int_y^\infty t^{x-1} e^{-t}\, dt$.

For Nakagami-m fading averaging (25) over the Nakagami-m PDF [14, eq. (2.20)], G_i^2 becomes

$$G_i^2 = \frac{m_i^{m_i} e^{m_i/\overline{\gamma}_i}\,\Gamma(1 - m_i, m_i/\overline{\gamma}_i)}{\overline{\gamma}_i^{m_i} N_{0,i}}. \qquad (27)$$

Clearly, for $m = 1$, (27) reduces to (26).

Substituting the infinite series representation of the modified Bessel function [22, eq. (9.6.10)] in the Rice PDF [14, eq. (2.15)], the gain in Rician fading can be expressed as

$$G_i^2 = \frac{2(1+K_i)\, e^{\frac{K_i+1}{\overline{\gamma}_i} - K_i}}{\overline{\gamma}_i N_{0,i}} \times \sum_{n=0}^{\infty} \frac{K_i^n (1+K_i)^n}{n!\, \overline{\gamma}_i^n} \Gamma\left(-n, \frac{K_i+1}{\overline{\gamma}_i}\right). \qquad (28)$$

The infinite series in (28) converges rapidly and it turns out that approximtely ten terms are necessary to achieve a third significant digit accuracy.

VII. Performance Evaluation Results

In this section, various performance evaluation results obtained by numerical and simulations techniques are presented. These results have verified the mathematical analysis and show the accuracy of the proposed performance bounds for the multihop system under consideration. We focus -without loss of generality- on the i.d. scenario, which means same average SNRs and severity parameter for all hops and consequently the same fixed gain ("blind" or "semi-blind") for all the intermediate nodes. In Fig. 1, the normalized average end-to-end SNR is plotted versus the number of hops N for several values of mean SNR $\overline{\gamma}$ and for $m = 3$. Monte Carlo simulations were also performed and their results are depicted in the same figure showing the accuracy and the tightness of the proposed upper bound. Moreover, as it was expected, the normalized average end-to-end SNR decreases with an increase in the number of hops. Fig. 2 depicts error BER performance of BPSK in Nakagami-m fading. A mean order $[5/6]$ of the Padé approximants is adequate to meet accuracy at the sixth significant digit. Furthermore, the accuracy and tightness of the proposed bound for the BER, compared to the simulations especially at low SNRs (< 10 dB), is evident. Moreover, the maximum deviation between the bound and the simulations is about 0.5 dB at BER 10^{-4}. The BER for DPSK in Rician fading is plotted in Fig. 3. Curves from simulations are plotted only for $N = 4$ to avoid entanglement. Finally, in Fig. 4, the end-to-end outage probability is plotted versus the inverse normalized threshold, $\overline{\gamma}/\gamma_{th}$, for $m = 3$ and several values of N. Once again, it is observed here that the proposed lower bounds are accurate and tight, especially at low SNRs.

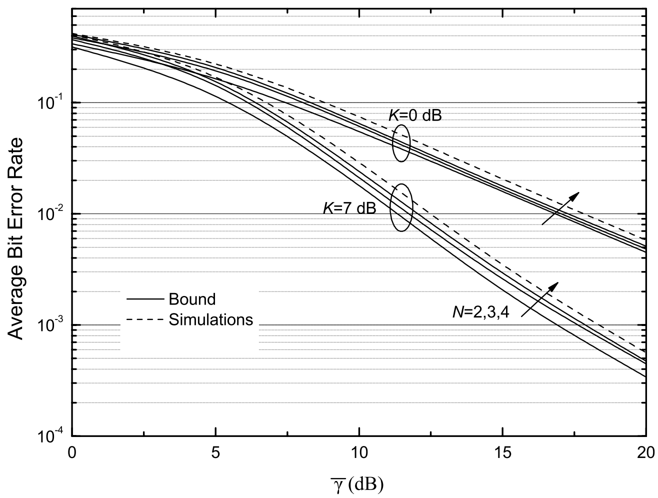

Fig. 3. Error performance for DPSK in Rice fading.

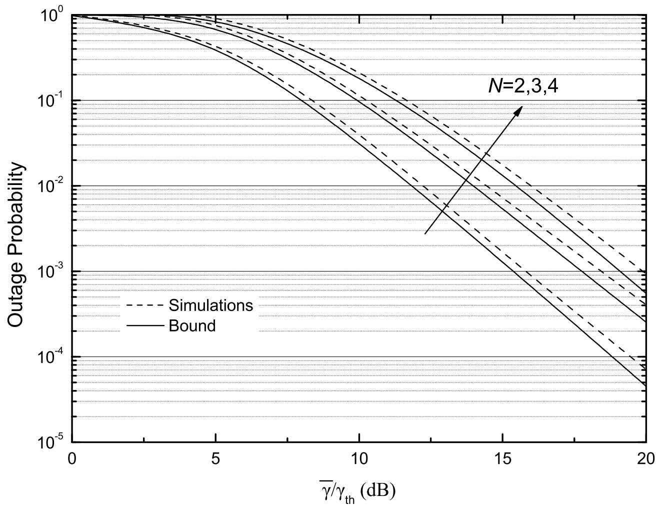

Fig. 4. Outage probability in Nakagami-m fading with $m = 3$.

VIII. Conclusions

The end-to-end SNR for multihop wireless communications systems with non-regenerative fixed-gain relays was derived and upper bounded using the well-known inequality between harmonic and geometric mean of positive RVs. Using this bound, simple closed-form expressions were given for the moments of the end-to-end SNR, in Rayleigh, Nakagami-m, and Rice fading. Moreover, the outage performance and the average error probability were studied, for several coherent and non-coherent modulation schemes using the MGF approach. Numerical and computer simulations shown the accuracy and the tightness of the proposed bounds, especially at low SNRs. The analysis presented in this paper can be easily extended to other fading channel models, such as Nakagami-q or Weibull.

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